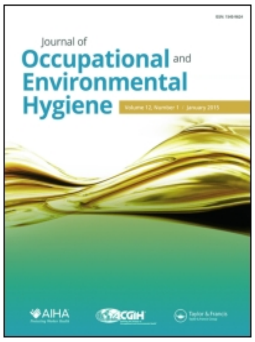

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Metal Exposures at three U.S. electronic scrap recycling facilities

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ABSTRACT
Many metals found in electronic scrap are known to cause serious health effects, including but not limited to cancer and respiratory, neurologic, renal, and reproductive damage. The National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention performed three health hazard evaluations at electronic scrap recycling facilities in the U.S. to characterize employee exposure to metals and recommend control strategies to reduce these exposures. We performed air, surface, and biological monitoring for metals. We found one overexposure to lead and two overexposures to cadmium. We found metals on non-production surfaces, and the skin and clothing of workers before they left work in all of the facilities. We also found some elevated blood lead levels (above 10 micrograms per deciliter), however no employees at any facility had detectable mercury in their urine or exceeded 34% of the OELs for blood or urine cadmium. This article focuses on sampling results for lead, cadmium, mercury, and indium. We provided recommendations for improving local exhaust ventilation, reducing the recirculation of potentially contaminated air, using respirators until exposures are controlled, and reducing the migration of contaminants from production to non-production areas. We also recommended ways for employees to prevent taking home metal dust by using work uniforms laundered on-site, storing personal and work items in separate lockers, and using washing facilities equipped with lead-removing cleaning products.

KEYWORDS
Cadmium; e-scrap; electronic scrap recycling; electronic waste; lead; used electronics

Introduction

Electronic wastes are items such as discarded computers, office electronic equipment, mobile phones, and television sets. The electronic scrap (also known as e-scrap, e-waste, or e-recycling) industry repairs these items for reuse, dismantles the items to remove valuable components such as copper or precious metals (e.g., silver, gold), shreds the electronics, and separates the metals from the plastics for recycling.

Commonly encountered recycling activities include receiving, sorting (Figure 1), testing, refurbishing, dismantling, and shredding (Figure 2). Specialized recycling activities include processing cathode ray tubes (CRTs), batteries, and fluorescent bulbs.[1] In this publication, dismantling refers to disassembling an electronic item to gain the maximum amount of recyclable materials. In the facilities that we evaluated, dismantling was usually done manually by employees who separated electronic components, such as circuit boards, hard drives, copper wiring, and other parts that contain valuable materials to be recovered and re-used. In contrast, shredding electronic equipment was a multistage process, requiring both automated and manual tasks to separate different materials (i.e., copper, aluminum, plastic, and ferrous metals). Although CRTs may be collected by many e-scrap recycling facilities, they are only processed at facilities equipped to handle the leaded glass in the CRT.[1] In CRT processing, employees manually break off the glass-encased neck (also called a "yoke," the part of the CRT that contains the copper-containing electron gun) by tapping it with a hammer. In most instances, employees manually remove the CRT metal support band that covers the seam between the nonlead front panel glass and leaded funnel glass. The employee removes unwanted labels and adhesives, cuts the CRT glass using a diamond-bladed cutting machine, and then

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

Figure 1. Battery sorting and removing batteries from the packaging.

manually separates the leaded funnel glass from the nonlead front panel glass. The CRT glass may be further cut and shredded, and lead and nonlead glass pieces separated.

Aside from ferrous metals, the most common metals in electronics include lead, cadmium, nickel, chromium, mercury, beryllium, indium, cobalt, and copper. Electronics may also contain rare earth elements, polychlorinated biphenyls, and flame retardants. Recycling electronics can expose employees to metals and other hazardous substances and conditions.[2–6] Chronic exposure to metals found in e-scrap recycling facilities can have serious health effects, including but not limited to cancer and respiratory, neurologic, renal, and reproductive damage. Furthermore, take-home exposure to lead has been documented in the U.S. e-scrap recycling industry.[3,7]

This article summarizes work performed by the National Institute for Occupational Safety and Health (NIOSH) Health Hazard Evaluation (HHE) Program in three e-scrap recycling facilities. Our objectives were to: (1) describe the use of exposure controls; (2) measure employee exposures to metals and assess exposure pathways via airborne and surface samples and biomarkers of exposure; and (3) recommend ways to reduce or eliminate metal exposures.

Figure 2. Sorters removing non-plastic and non-metal pieces (i.e., rubber pieces), green board pieces, and copper at the shredding machine.

Methods

NIOSH performed HHEs at three facilities,[3–5] (A, B, and C), as described in Table 1. We toured the facilities and observed work processes and practices, and personal protective equipment (PPE) use. We interviewed employees at all three facilities about their job duties and PPE use. We reviewed the facilities' health and safety programs and observed engineering controls where present. We collected personal air samples; hand, skin, and clothing wipe samples; and blood and urine samples for metals from employees. We also collected surface wipe samples and area air samples for metals. We individually notified participants in writing of their results and shared summary information with the employer and employee representatives at each facility.

Air sampling

We took personal and area air samples for elements (metals and minerals) following NIOSH Method 7303 in facilities A and C.[8] Although we analyzed the samples for the 32 elements listed in this method, this manuscript focuses on beryllium, cadmium, indium, and lead. To account for wall loss, each sample cassette was wiped with a wet smear tab to collect particles remaining on the inside wall of the cassette. The smear tab was then analyzed along with the sample filter as recommended by NIOSH.[8] We added indium to our elemental scan for samples from facility C after learning of its use in some electronics. We collected full shift area air samples around the shredder at facility C during two shifts; once while the shredder was running and once when it was not. Samples were collected in the exact same location each shift. We collected personal and area air samples for elemental mercury using NIOSH Method 6009 in facilities A and B because employees in these facilities were recycling fluorescent bulbs, which contain mercury.[8] Although we did not collect air samples for metals at facility B, we reviewed the company's industrial hygiene reports for metals from previous years.

Surface wipe sampling

We collected surface wipe samples for metals and other elements in production and non-production areas (i.e., break rooms, locker rooms, and offices), on clothing, and on employees' skin at all facilities. We used premoistened

Table 1. Characteristics of three electronic scrap recycling facilities at the time of the evaluation.

Characteristics	Facility A	Facility B	Facility C
General facility characteristics			
Certifications	e-Stewards, R2	e-Stewards, R2	R2
Number of employees	80	80	10
Primary languages spoken	English, Spanish, French	English and Hmong	English, Pohnpei
Key processes performed	Electronic dismantling Automated CRT cutting Electronics shredding Batteries sorting	Electronic dismantling CRT and electronics shredding Batteries sorting	Electronic dismantling Electronics shredding Batteries sorting
Engineering controls			
General ventilation	Exterior wall-mounted fans with filters in dismantling area	Exterior wall-mounted fans in the dismantling area	Exterior wall-mounted fans in the warehouse
Natural ventilation	Through open garage doors	Through open garage doors	Through open garage doors
Local exhaust ventilation	CRT cutting machine recirculated air through MERV-13 filter No LEV on the shredder Downdraft table	Bag-style dust collection system in CRT shredding area Extraction hoods located where batteries where dismantled	LEV in the shredder with recirculated air through MERV-15 filters
Administrative controls			
Drinking in production areas allowed	Yes	Yes	Yes
Lockers available	Yes for CRT processors	No	No
Separate clean and dirty lockers	No	No	No
Showers available	No	Yes for shredders	No
Lead-removing soap available	No	No	No
Dry sweeping performed	Yes	Yes	Yes
Uniforms provided	Yes for CRT processors and maintenance	Yes for shredders	No
Uniforms laundered by facility contractor	Yes	Yes	No
Lead hazard control program, including BLL and air sampling	Yes for CRT operators and maintenance	Yes for shredders	No
Air monitoring program for other metals	No	No	No
Personal protective equipment			
Employees required to use respirators[a]	CRT processors and maintenance	CRT Shredders	No
Employee voluntary use of respirators (disposable N95)	Dismantlers Shredders Sorters	Dismantlers Sorters	Shredders
Hearing protection	Not used	Used throughout production areas	Used when the shredder was on
Cut resistant gloves and sleeves	Yes	Yes	Yes
Safety glasses	Yes	Yes	Yes

[a]CRT processors and maintenance employees in facility A and CRT shredders in facility B used elastomeric half-mask air purifying respirators with P100 filters.

Ghost Wipe® towelettes and, when possible, a 10-square centimeter disposable cardboard template to outline the surface that we sampled. For uneven or irregular surfaces, such as clothing, we estimated a similar sized sample area. We collected the samples from the skin and/or clothing of the employees before they left work at the end of their shift. For hand wipes at facilities A and B we asked employees to wipe both hands (i.e., wrist down to fingers including palm and back of the palm) for at least 30 sec using the same wipe. At facility C, following a procedure outlined by Esswein et al.,[9] we wiped the employees' dominant hand for 30 sec. All wipe samples were quantitatively analyzed using NIOSH Method 9102.[8] Indium was added to the elemental scan when analyzing samples from facility B and C. At facility B we also collected wipe samples for mercury on work surfaces and employees' skin and clothing using a Whatman LabSales Inc. No. 41 filter. We collected and analyzed these wipe samples following the Occupational Safety and Health Administration (OSHA) Method ID-145.[10]

Biological monitoring

We tested employees' blood for lead and cadmium, and their urine for mercury and cadmium. All potential study participants signed a consent form prior to having their blood and urine samples collected. We followed standard precautions for working with blood and blood products.[11,12] Urine samples were collected in metal-free cups and then transferred in the field to 30-mL acid-washed centrifuge tubes. Blood and urine samples were analyzed by an OSHA-approved contract laboratory. Mercury and cadmium results were standardized to grams of creatinine to account for differences in urine concentration.

Blood cadmium levels measure exposure in the past few months,[13,14] while urinary cadmium levels can measure longer-term exposure (several years).[13] Urine mercury levels have a half-life of about 90 days at the exposure levels encountered in our evaluations.[13] In most cases, an individual's blood lead level (BLL) is a good indication of recent exposure to lead because the half-life of lead is 1–2 months.[13,15,16] We defined an elevated BLL as greater than 10 micrograms per deciliter (µg/dL) rather than the OSHA limit of 40 µg/dL.[17–19] The OSHA permissible exposure limit may prevent overt symptoms of lead poisoning, but does not protect workers from lead's contributions to conditions such as hypertension, renal dysfunction, reproductive, and cognitive effects which can be seen at BLLs of as low as 5–10 µg/dL.[20]

Data analysis

We compared our personal air sampling, blood, and urine results to their relevant occupational exposure limits (OELs). There are no OELs for metals on surfaces or skin. The United States Environmental Protection Agency and the United States Department of Housing and Urban Development limit lead on surfaces in public buildings and in child-occupied housing to less than 40 µg of lead per square foot.[21,22] OSHA requires in its substance-specific standard for lead that all surfaces be maintained as free as practicable of accumulations of lead according to 29 CFR 1910.1025(h)(1).[12] For facility B, end-of-shift hand wipes collected on shred room employees (n = 12) were compared to those from teardown employees (n = 10) by a two-way t-test of the logarithm of the means using American Industrial Hygiene Association IHstats V229, because the data had a log-normal distribution.

Results

Table 1 summarizes the general facility descriptions and controls at each facility. All facilities were in warehouses with limited local exhaust ventilation (LEV) and general ventilation. The facilities differed in how much they isolated their aerosol generating tasks, such as material shredding, from other recycling operations. All three facilities recirculated potentially contaminated air. At facility B the shredder was in a separate room, thereby reducing the potential for exposing employees in other departments to high concentrations of lead and other contaminants. Facility A did not have a separate room for the shredder. The CRT cutting area and CRT grinding and buffing areas were located in the main production area and the recirculated air passed through filters with a minimum efficiency reporting value (MERV) of 13 prior to being exhausted. In addition, the glass breaking and dismantling areas were not separated from the rest of the facility, and the shredder did not have LEV. Although the shredder at facility C was located at the far end of the facility, it was not separated from the other operations. The LEV air passed through eight MERV 15 nanofiber filters prior to being recirculated back into the work area. Similarities among all facilities included that they

Table 2. Full-shift personal air monitoring results by facility.

	Number of samples collected	Lead concentration range (µg/m³)	Cadmium concentration range (µg/m³)	Sample duration (min)
Facility A				
Shredder sorting	9	(1.6)–67	ND–0.84	448–503
CRT buffing and grinding[a]	5	9.8–27	0.18–10	460–497
CRT operators	6	6.1–16	(0.090)†–0.34	317–493
CRT dismantling	8	2.1–5.3	ND–0.84	377–495
Maintenance	5	(1.4)–4.1	ND–0.10	435–492
Baler, battery bulb sorting	5	(0.9)–3.9	ND–(0.065)	457–470
MDC[b]		0.6	0.02	
MQC		2.0	0.090	
Facility C				
Shipping, receiving, shredding	12	(0.34)–3.3	ND–0.08	431–491
Battery sorters	13	(0.2)–3.3	ND–(0.06)	441–483
Dismantling	9	(0.37)–(1.2)	ND–0.14	445–486
MDC[b]		0.2	0.03	
MQC		1.3	0.080	
OSHA PEL		50	5	
NIOSH REL		50	Carcinogen	
ACGIH TLV		50	10	

ND = not detected, below the minimum detectable concentration (MDC). Concentrations shown in parentheses were above the MDC but below the minimum quantifiable concentration (MQC), meaning that there is more uncertainty with these values.
[a]CRT buffing and grinding included employees performing CRT buffing only or CRT buffing and grinding.
[b]The MDC and MQC were calculated based on an average sample volume of 465 L for facility A and 783 L for facility C.

had health and safety programs in place, provided PPE including respirators, gloves, and cut resistant sleeves, and had respiratory protection programs.

Results for lead and cadmium in air samples at facility A are in Table 2. Lead concentrations in personal air samples ranged from 0.9–67 µg/m^3. Cadmium concentrations ranged from not detectable to 10 µg/m^3. Of the nine personal air samples we collected on employees in the shredder sorting area, we measured one exposure to lead above the OSHA Permissible Exposure Limit (PEL). One CRT buffing and grinding employee had an airborne lead exposure of 27 µg/m^3, which is near the OSHA action limit of 30 µg/m^3.[12] We measured two exposures above the OSHA PEL to cadmium on the five CRT buffing and grinding employees that we sampled. Overall, the CRT operator and CRT buffing and grinding employees had the highest airborne lead and cadmium exposures. Employees in shredder sorting had the next highest lead exposures. Personal air sample results for other metals, including mercury and chromium, were well below applicable OELs. Beryllium (MDC = 0.0020 µg/m^3) and cobalt (MDC = 0.065 µg/m^3) were not detected. Area air concentrations of metals were higher in production areas compared to non-production areas. For example, concentrations were higher near the CRT glass breaking area (e.g., lead 8.3 µg/m^3, cadmium 0.22 µg/m^3) than in the employee break rooms (e.g., lead 0.77 µg/m^3; cadmium was not detected above the MDC of 0.02 µg/m^3).

At facility B, we did not detect airborne mercury (MDC = 0.0099 µg/m^3 for mercury particulate and 0.0023 µg/m^3 for mercury vapor). Consultant reports indicated that in the past some shredding employees had exposures above the OSHA action level of 30 µg/m^3 or the PEL of 50 µg/m^3.[12] The employees in the other production areas had not been evaluated by the consultant.

Airborne lead and cadmium results for facility C are shown in Table 2. Airborne lead concentrations ranged from 0.2 to 3.3 µg/m^3 while cadmium concentrations ranged from not detectable to 0.14 µg/m^3. None of the 34 personal exposure measurements exceeded applicable OELs and, with the exception of beryllium, results were at least an order of magnitude below the lowest OEL. One personal air sample result for beryllium, collected on an employee in the dismantling area (0.04 µg/m^3) was near the most protective OEL of 0.05 µg/m^3 recommended by the American Conference of Governmental Industrial Hygienists.[23] Indium was not detected above the MDC of 0.4 µg/m^3 in any of the air samples. Full shift area air sample results in facility C were higher when the shredder was operating (e.g., lead 8.1 µg/m^3, cadmium 0.35 µg/m^3) than when it was not running (e.g., lead and cadmium were not detectable).

Summary results for metals on skin, clothing, and work surfaces are in Table 3. We found metals on non-production surfaces in all facilities, indicating migration from production to non-production areas. We detected lead on the skin and clothing of employees before they left all facilities. At facility B, dismantling employees had approximately 3 times more lead and 33 times more cadmium than the CRT shredding employees on their hands before leaving work at the end of the shift. This is likely because the CRT shredding employees showered and changed clothes before leaving work, while dismantling employees only washed their hands. We did not find mercury on the skin (hands, forearm, neck) of the CRT shredder employees (after showering) at facility B, but did find mercury on their street clothes. We also found mercury on one of the skin wipe samples from a facility B dismantling employee who did not shower.

The biomonitoring results for the three facilities are in Table 4. BLLs ranged from not detected to 14 µg/dL at facility A and from not detected to 13 µg/dL at facility B. Two of the nine CRT processors at facility A and 2 of the 13 dismantlers at facility B had elevated BLLs. We did not detect lead in employees' blood at facility C. No employees at any facility had detectable mercury in their urine or exceeded 34% of the OELs for blood or urine cadmium.

Discussion

We found a few airborne overexposures to lead and cadmium above applicable OELs (2.7% of 72 personal air samples) and only one sample for beryllium near its OEL. We identified employee overexposures to lead when compared to current health-based guidance (8.5% of 47 biological samples). Although in these evaluations we identified lead and cadmium as the primary contaminants of concern due to the airborne and/or biological overexposures, given the variability of the e-scrap recycling stream additional metals can be present.

Our first objective was to document the exposure controls in place at the facilities we assessed. The three facilities we visited used a wide range of exposure controls. Facility A relied primarily on administrative controls and PPE. They had written health and safety programs and had performed air sampling, conducted employee medical surveillance, and provided employees with PPE. Facility B used engineering and administrative controls in the shred room and provided employees with PPE. However, despite these actions some dismantler employees in facility B had high BLLs, suggesting that lead exposures were not adequately controlled outside of the shred room. Employees at facility C had low airborne metal exposures and biological levels. Facility C's e-scrap throughput was less than that at facilities A and B, which likely

Table 3. Surface and skin wipe sampling for lead, cadmium, and mercury.

	Lead # Positive of total	Cadmium # Positive of total	Mercury # Positive of total
Facility A			
Hands or other skin	8 of 12	Not collected	Not collected
Clothes	12 of 13	Not collected	Not collected
Non-production area	13 of 13	13 of 13	Not collected
Production area	10 of 10	10 of 10	Not collected
Facility B			
Hands or other skin	31 of 31	25 of 31	0 of 4
Clothes	1 of 1	1 of 1	1 of 1
Non-production area	18 of 23	12 of 23	8 of 23
Production area	6 of 6	5 of 6	3 of 6
Facility C			
Hands or other skin	6 of 6	6 of 6	Not collected
Clothes	2 of 2	2 of 2	Not collected
Non-production area	8 of 12	9 of 12	Not collected
Production area	8 of 8	8 of 8	Not collected
Limit of detection, (µg/sample)	0.3–0.60	0.01–0.05	0.007–0.02

Table 4. Biomonitoring results by facility.

	Number of employees	Blood lead levels (µg/dL)	Blood cadmium (µg/dL)	Urine cadmium (µg/g/creatine)	Urine mercury (µg/g/creatine)
Facility A					
Maintenance, CRT operator, buffers, grinders	9	5.3–14	ND–1.0	0.1–0.8	ND
Baler, shredder, battery	5[a]	ND–8.8	ND–1.2	0.3–1.0	ND
Facility B					
CRT shredders	7	ND–4.6	ND–1.7	0.1–0.9	ND
Dismantlers	13	ND–13	ND–0.9	ND–1.1[b]	ND
Forklift drivers and battery and bulb employees	3	6.6–9.4	ND–1.5	ND–0.9	ND
Facility C					
Shipping, receiving, shredding	5	ND	0.5–1.0	Not collected	Not collected
Dismantling	3	ND	0.6–1.5	Not collected	Not collected
Battery sorters	2	ND	0.5–0.6	Not collected	Not collected
Limit of detection		3.0	0.5	0.1	5.0
Exposure limits		10[c]	5 (OSHA)	3 (OSHA)	20 (ACGIH)

ND = not detected.
[a]One employee declined blood testing.
[b]Two employees did not have their urine cadmium levels checked because they had not worked at this facility long enough for cadmium to build up in their kidneys.
[c]BLL overexposure defined as greater than 10 µg/dL.[17–19, 25]

contributed to their lower air and biological sampling results. Practices at all three facilities that could contribute to take-home exposures included not changing work clothes before going home, using the same locker to store contaminated PPE and clothing with personal items, not using work uniforms, laundering uniforms at home, and not requiring that all employees shower before going home.

Our second objective was to measure exposures to metals in air, on surfaces, and in biological samples. Employees in all three e-scrap recycling facilities we evaluated had occupational exposures to metals in the air and on surfaces and had metals on their hands and/or clothes when leaving the facility. Although we did measure other metals, the ones that we found in the highest concentrations relative to their OELs were lead and cadmium. Our findings are similar to those at three e-scrap recycling facilities in Sweden, but researchers there also documented airborne overexposures to nickel.[6] In e-scrap recycling, exposures could vary greatly depending on the type of e-scrap being recycled. We found one employee's airborne exposure that approached the OEL for beryllium. Beryllium can be found in older printed circuit boards, which is the likely cause of this elevated sample result.[24] Mercury is found in fluorescent lights, certain batteries, telecommunication equipment, and certain flat panel screens. Facility B processed mercury-containing light bulbs and mercury was found on the skin and clothes of some employees. Last, flat panel displays and touch screens can contain indium or indium tin-oxide. These items were not being shredded when we collected our samples so it is not surprising that our personal air samples did not detect indium.

In facility A, two employees had elevated BLLs and three employees had airborne overexposures (1 to lead and 2 to cadmium). This facility did not have LEV on the shredder, which is where our area air samples detected the highest airborne lead concentrations. Although CRT operators and maintenance employees were included in the facility's written lead compliance program, the facility did not have a written compliance program for cadmium. OSHA requires a written compliance program for cadmium when cadmium exposure levels exceed the OSHA PEL of 5 μg/m^3 (29 CFR 1910.1027). Lead and cadmium compliance programs should include a description of each operation where exposures occur and how the employer will achieve compliance with the standard, among other requirements.[12]

Two employees at facility B had elevated BLLs. The facility assumed the primary exposure to lead was from the CRTs in the shredding area. Because it was separated from other parts of the facility, only the shredding employees were provided work uniforms and required to shower prior to going home. Interestingly, the dismantling employees had a significantly higher concentration of metals on their hands after washing than the CRT shredding employees did after showering. In addition, only the dismantling employees had elevated BLLs.

No employees at facility C had elevated BLLs. The low BLLs and blood cadmium results from facility C could be explained by one or more factors including the low quantity of material fed into the shredder (the shredder ran, at most, 3 days per month) and/or the use of LEV at the shredder. Because we found lead and cadmium in our environmental samples, higher blood lead and blood cadmium levels may be possible if the facility increases shredding operations.

Our third objective was to recommend controls to reduce or eliminate workplace metal exposures. We provided recommendations based on the hierarchy of controls to each facility.[3–5] These recommendations included not recirculating potentially contaminated air back into the facility and adding or improving LEV. We recommended changing work practices to decrease the migration of contaminants from production to non-production areas. We recommended that facilities processing CRTs or shredding lead-containing materials implement a lead compliance program to identify potentially exposed employees, which would include BLL testing, periodic air monitoring, and surface wipe sampling to assess contaminant migration. We also recommended following the latest health-based guidance on blood lead levels.

We recommended that the facilities provide work uniforms that are changed onsite and then laundered by the company, showering facilities, and onsite changing rooms with separate lockers for clean and dirty clothes. We also recommended requiring employees to wash their hands and face with a lead-removing product such as soap or wipes prior to eating, drinking, smoking, and leaving the facility. NIOSH research shows that washing hands with soap and water is not completely effective in removing lead (and other toxic metals) from the skin.[25] In addition, as OSHA prescribes, an employer with workplace exposures to lead must implement regular and effective cleaning of surfaces in areas such as change areas, storage facilities, and lunchroom or eating areas to ensure they are as free as practicable from lead contamination.[12] If overexposures were documented, we also recommended using respirators until exposures are controlled below the OELs.

Because the makeup of e-scrap streams can be unpredictable, we recommend identifying the types of metals possibly present in the material prior to recycling. Carefully tracking the electronic components can help to identify the hazardous metals that enter the waste stream.

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Disclaimer

The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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